

LIGHT EMITTING DIODES WITH IMPROVED LIGHT EXTRACTION
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RELATED APPLICATIONS

This application is a Continuation-In-Part of U.S. Patent Application Serial No. 09/660317 filed on September 12, 2000, which is herein incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to light emitting devices and more particularly to light emitting diodes with enhanced light extraction efficiency.

2. Description of the Related Art

- The light extraction efficiency of a light emitting diode (LED) is defined as the ratio of the LED's external quantum efficiency to the LED's internal quantum efficiency. Typically, the light extraction efficiency of a packaged LED is substantially less than one, i.e., much of the light generated in the LED's active region never reaches the external environment.

- Light extraction efficiency is reduced by total internal reflection at interfaces between the LED and surrounding material followed by reabsorption of the totally internally reflected light in the LED. For example, for a cubic geometry LED on a transparent substrate encapsulated in epoxy, the refractive index (n) at the emission wavelength changes from a value of, for example, $n_{\text{semi}} \sim 3.5$ in the LED semiconductor to $n_{\text{epoxy}} \sim 1.5$ in the epoxy. The corresponding critical angle for total internal reflection of light incident on the epoxy encapsulant from the LED semiconductor of this example is $\theta_C = \arcsin(n_{\text{epoxy}}/n_{\text{semi}}) \sim 25^\circ$. Neglecting scattering and multiple reflections, light emitted over 4π steradians from a point in the active region of the cubic LED crosses a semiconductor / epoxy encapsulant interface only if it is emitted into one of six narrow light cones, one for each interface, with each light cone having a half angle equal to the critical angle. Additional losses due to total internal reflection can occur at the epoxy / air interface. Consequently, an efficient conventional geometry (for example, rectangular parallelepiped) transparent substrate AlInGaP LED encapsulated in epoxy, for example, may have an external quantum efficiency of only $\sim 40\%$, despite having an internal quantum efficiency of nearly 100 %.

- The effect of total internal reflection on the light extraction efficiency of LEDs is further discussed in U.S. Patents 5,779,924; 5,793,062; and 6,015,719 incorporated herein by reference.

In one approach to improving light extraction efficiency, LEDs are ground into hemispherical shapes. Light emitted from a point in the active region of a hemispherically shaped LED intersects the hemispherical interface at near normal incidence. Thus, total internal reflection is reduced. However, this technique is tedious

and wasteful of material. In addition, defects introduced during the grinding process may compromise the reliability and performance of the LEDs.

- 5 In another approach, LEDs are encapsulated (encased) in a material with a dome or hemispherically shaped surface. For example, the epoxy encapsulant of the above example may be dome shaped to reduce losses due to total internal reflection at the epoxy encapsulant / air interface. However, shaping the surface of a low refractive index encapsulant such as epoxy does not reduce losses due to total internal reflection at the semiconductor / low index encapsulant interface. Moreover, epoxy encapsulants typically have coefficients of thermal expansion that poorly match those of the
- 10 semiconductor materials in the LED. Consequently, the epoxy encapsulant subjects the LED to mechanical stress upon heating or cooling and may damage the LED. LEDs are also encapsulated in dome shaped high index glasses, which increase the critical angle for the semiconductor / encapsulant interface. Unfortunately, optical absorption in high index glasses and mechanical stress typically degrade the performance of an LED
- 15 encapsulated in such glass.

What is needed is a method for increasing the light extraction efficiency of light emitting diodes which does not suffer from the drawbacks of previous methods.

SUMMARY

- 20 Light emitting devices with improved light extraction efficiency are provided. The light emitting devices have a stack of layers including semiconductor layers comprising an active region. The stack is bonded to a transparent optical element.

- In some embodiments, the optical element is a lens, for example a hemispheric lens or a Fresnel lens. In other embodiments, the optical element is an optical
- 25 concentrator using, for example, a total internal reflector (TIR). The optical element is formed, for example, from optical glass, III-V semiconductors, II-VI semiconductors, group IV semiconductors and compounds, metal oxides, metal fluorides, diamond, sapphire, zirconium oxide, yttrium aluminum garnet, or combinations thereof. The

refractive index of the optical element for light emitted from the active region is preferably greater than about 1.5, more preferably greater than about 1.8.

- 5 In one embodiment, the transparent optical element is directly bonded to at least one of the semiconductor layers of the stack. In another embodiment, the transparent optical element is directly bonded to a transparent superstrate disposed above the semiconductor layers. The transparent superstrate preferably has a refractive index for light emitted from the active region greater than about 1.8.

- 10 In other embodiments, the light emitting device includes a transparent bonding layer disposed between the optical element and a surface of the stack. The transparent bonding layer bonds the optical element to the surface of the stack. In one embodiment, the surface includes a surface of one of the semiconductor layers. In another embodiment, the surface includes a surface of a transparent superstrate layer disposed above the semiconductor layers. The transparent bonding layer is formed, for example, from metals, phosphide compounds, arsenide compounds, antimonide compounds, nitride compounds, or any of the materials listed above for the transparent optical element. In 15 one embodiment, the transparent bonding material has an index of refraction for light emitted from the active region greater than about 1.5, preferably greater than about 1.8.

- A method of bonding a transparent optical element to a light emitting device having a stack of layers including semiconductor layers comprising an active region is 20 provided. The method includes elevating a temperature of the optical element and the stack and applying a pressure to press the optical element and the stack together. In one embodiment, the method also includes disposing a layer of a transparent bonding material between the stack and the optical element. The bonding method can be applied to a pre-made optical element or to a block of optical element material which is later formed or 25 shaped into an optical element such as a lens or an optical concentrator.

Bonding a high refractive index optical element to a light emitting device improves the light extraction efficiency of the light emitting device by reducing loss due to total internal reflection. Advantageously, this improvement can be achieved without the use of an encapsulant.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A is a schematic diagram of an optical element and a light emitting diode to be bonded to each other in accordance with an embodiment of the present invention.

5 Figure 1B is a schematic diagram of an optical element bonded with a bonding layer to a light emitting diode in accordance with an embodiment of the present invention.

Figure 1C is a schematic diagram of an optical element bonded to a light emitting diode in accordance with another embodiment of the present invention.

10 Figure 1D is a schematic diagram of an optical concentrator bonded to a light emitting diode in accordance with another embodiment of the present invention.

Figure 2 is a schematic diagram of an optical element directly bonded to a light emitting diode in accordance with an embodiment of the present invention.

15 Figure 3 is a schematic diagram of an optical element bonded with a bonding layer to a light emitting diode having beveled sides in accordance with an embodiment of the present invention.

Figure 4 is a schematic diagram of an optical element bonded with a bonding layer to a light emitting diode having substrate and superstrate layers in accordance with an embodiment of the present invention

20 Figure 5 is a schematic diagram of an optical element directly bonded to a light emitting diode having substrate and superstrate layers in accordance with an embodiment of the present invention

Figure 6 is a schematic diagram of an optical element bonded with a bonding layer to a light emitting diode having a "flip chip" geometry in accordance with an embodiment of the present invention.

Figure 7 is a schematic diagram of an optical element directly bonded to a light emitting diode having a "flip chip" geometry in accordance with an embodiment of the present invention

- 5 Figure 8 is a schematic diagram of an optical element bonded with a bonding layer to a light emitting diode having an active region substantially perpendicular to the optical element.

Figure 9 is a schematic diagram of an optical element bonded directly to a light emitting diode having an active region substantially perpendicular to the optical element.

- 10 Figure 10 is a schematic diagram of a light emitting diode located in a recess of a surface of an optical element to which it is directly bonded.

Figure 11 is a schematic diagram of a light emitting diode located in a recess of a surface of an optical element to which it is bonded with a bonding layer.

DETAILED DESCRIPTION

- 15 Figure 1A depicts a transparent optical element 2 and a light emitting diode (LED) die 4 to be bonded to each other in accordance with an embodiment of the present invention. In Figure 1B, in accordance with one embodiment of the present invention, transparent optical element 2 is bonded to LED die 4 with a transparent bonding layer 6.

- 20 The term "transparent" is used herein to indicate that an optical element so described, such as a "transparent optical element," a "transparent bonding layer," a "transparent substrate," or a "transparent superstrate" transmits light at the emission wavelengths of the LED with less than about 50%, preferably less than about 10%, single pass loss due to absorption or scattering. The emission wavelengths of the LED may lie in the infrared, visible, or ultraviolet regions of the electromagnetic spectrum. One of
25 ordinary skill in the art will recognize that the conditions "less than 50% single pass loss" and "less than 10% single pass loss" may be met by various combinations of transmission path length and absorption constant. As used herein, "optical concentrator" includes but

is not limited to total internal reflectors, and includes optical elements having a wall coated with a reflective metal or a dielectric material to reflect or redirect incident light.

LED die 4 illustrated in Figures 1A and 1B includes a first semiconductor layer 8 of n-type conductivity (n-layer) and a second semiconductor layer 10 of p-type conductivity (p-layer). Semiconductor layers 8 and 10 are electrically coupled to active region 12. Active region 12 is, for example, a p-n diode junction associated with the interface of layers 8 and 10. Alternatively, active region 12 includes one or more semiconductor layers that are doped n-type or p-type or are undoped. N-contact 14 and p-contact 16 are electrically coupled to semiconductor layers 8 and 10, respectively. Active region 12 emits light upon application of a suitable voltage across contacts 14 and 16. In alternative implementations, the conductivity types of layers 8 and 9, together with contacts 14 and 16, are reversed. That is, layer 8 is a p-type layer, contact 14 is a p-contact, layer 10 is an n-type layer, and contact 16 is an n-contact.

Semiconductor layers 8 and 10 and active region 12 are formed from III-V semiconductors including but not limited to AlN, AlP, AlAs, AlSb, GaN, GaP, GaAs, GaSb, InN, InP, InAs, InSb, II-VI semiconductors including but not limited to ZnS, ZnSe, CdSe, CdTe, group IV semiconductors including but not limited to Ge, Si, SiC, and mixtures or alloys thereof. These semiconductors have indices of refraction ranging from about 2.4 to about 4.1 at the typical emission wavelengths of LEDs in which they are present. For example, III-Nitride semiconductors such as GaN have refractive indices of about 2.4 at 500 nm, and III-Phosphide semiconductors such as InGaP have refractive indices of about 3.7 at 600 nm.

Contacts 14 and 16 are, in one implementation, metal contacts formed from metals including but not limited to gold, silver, nickel, aluminum, titanium, chromium, platinum, palladium, rhodium, rhenium, ruthenium, tungsten, and mixtures or alloys thereof. In another implementation, one or both of contacts 14 and 16 are formed from transparent conductors such as indium tin oxide.

Although Figures 1A and 1B illustrate a particular LED structure, the present invention is independent of the number of semiconductor layers in LED die 4, and independent of the detailed structure of active region 12. Also, LED die 4 may include,

for example, transparent substrates and superstrates not illustrated in Figures 1A and 1B. It should be noted that dimensions of the various elements of LED die 4 illustrated in the various figures are not to scale.

In one embodiment, a layer of bonding material is applied to a top surface 18 of LED die 4 (Figure 1A) to form transparent bonding layer 6 (Figure 1B) with which to bond optical element 2 to LED die 4. Transparent bonding layer 6 is, for example, about 10 Angstroms (Å) to about 100 microns (μm) thick. The bonding material is applied, for example, by conventional deposition techniques including but not limited to spinning, sputtering, evaporation, chemical vapor deposition (CVD), or as part of material growth by, for example, metal-organic chemical vapor deposition (MOCVD), vapor phase epitaxy (VPE), liquid phase epitaxy (LPE), or molecular beam epitaxy (MBE). Transparent bonding layer 6 is optionally patterned with, for example, conventional photolithographic and etching techniques to leave contact 14 uncovered by bonding material and thus to permit contact 14 to make electrical contact with optional metallization layer 20 on optical element 2. Metallization layer 20, in one embodiment a mesh and in other embodiments a continuous or patterned layer, for example, about 2 Å to about 5000 Å thick, transmits greater than about 10%, preferably greater than about 50%, of incident light and provides a physically accessible electrical contact coupled to contact 14. Metallization layer 20 is formed, for example, from metals or transparent conductors such as indium tin oxide.

In an alternative embodiment, transparent bonding layer 6 is formed on substantially flat surface 22 of optical element 2 or on the surface of metallization layer 20 and optionally patterned with, for example, conventional photolithographic and etching techniques to permit electrical contact between contact 14 and metallization layer 20. In another embodiment transparent bonding layers such as bonding layer 6 are formed on both surface 18 of LED die 4 and surface 22 of optical element 2. In other embodiments, contact 14 is not separately provided, and bonding layer 6 is patterned to permit electrical contact between metallization layer 20 and n-layer 8. In the embodiment shown in Figure 1C, neither contact 14 nor bonding layer 6 is separately provided, and metallization layer 20 additionally functions as a bonding layer. In other embodiments, contact 14 is not located on surface 18 and the metallization layer 20 is not used.

Though the following discussion assumes that bonding layer 6 is formed on LED die 4 rather than on surface 22 of optical element 2 or on both LED die 4 and surface 22, the process described below can be simply modified to implement the latter embodiments.

5 In one implementation, the bonding material from which transparent bonding layer 6 is formed is a high index optical glass, i.e., an optical glass having a refractive index greater than about 1.5 in the range of wavelengths emitted by active region 12. Preferably, the refractive index is greater than about 1.8. Transparent bonding layer 6 is formed, for example, from Schott glass SF59, a dense flint glass which has refractive
10 index (n) ~ 1.95 at ~ 600 nanometers (nm) and a glass transition temperature (T_G) $\sim 362^\circ\text{C}$. Alternatively, transparent bonding layer 6 is formed from high index optical glasses including but not limited to Schott glass LaSF 3, with $n \sim 1.81$ at ~ 600 nm and $T_G \sim 630^\circ\text{C}$; Schott glass LaSF N18, with $n \sim 1.91$ at ~ 600 nm and $T_G \sim 660^\circ\text{C}$; and mixtures thereof. These glasses are available from Schott Glass Technologies Incorporated, of
15 Duryea, PA. Bonding layer 6 may also be formed from a high index chalcogenide glass, such as (Ge,Sb,Ga)(S,Se) chalcogenide glasses, for example.

In other implementations, bonding layer 6 is formed from III-V semiconductors including but not limited to GaP ($n \sim 3.3$ at 600 nm), InGaP ($n \sim 3.7$ at 600 nm), GaAs ($n \sim 3.4$ at 500 nm), and GaN ($n \sim 2.4$ at 500 nm); II-VI semiconductors including but not
20 limited to ZnS ($n \sim 2.4$ at 500 nm), ZnSe ($n \sim 2.6$ at 500 nm), ZnTe ($n \sim 3.1$ at 500 nm), CdS ($n \sim 2.6$ at 500 nm), CdSe ($n \sim 2.6$ at 500 nm), and CdTe ($n \sim 2.7$ at 500 nm); group IV semiconductors and compounds including but not limited to Si ($n \sim 3.5$ at 500 nm), and Ge ($n \sim 4.1$ at 500 nm); organic semiconductors, metal oxides including but not limited to tungsten oxide, titanium oxide ($n \sim 2.9$ at 500 nm), nickel oxide ($n \sim 2.2$ at 500
25 nm), zirconium oxide ($n \sim 2.2$ at 500 nm), indium tin oxide, and chromium oxide; metal fluorides including but not limited to magnesium fluoride ($n \sim 1.4$ at 500 nm) and calcium fluoride ($n \sim 1.4$ at 500 nm); metals including but not limited to Zn, In, Mg, and Sn; yttrium aluminum garnet (YAG), phosphide compounds, arsenide compounds, antimonide compounds, nitride compounds, high index organic compounds; and mixtures
30 or alloys thereof.

Bonding layer 6 includes, in one implementation, luminescent material that converts light of wavelengths emitted by active region 12 to other wavelengths. The luminescent material includes, for example, conventional phosphor particles, organic semiconductors, II-VI or III-V semiconductors, II-VI or III-V semiconductor quantum dots or nanocrystals, dyes, polymers, and materials such as GaN that luminesce from defect centers. If bonding layer 6 includes conventional phosphor particles, then bonding layer 6 should be thick enough to accommodate particles typically having a size of about 5 microns to about 50 microns.

In one implementation, bonding layer 6 is formed from a high index material (refractive index at the LED's emission wavelengths greater than about 1.5, preferably greater than about 1.8) having a refractive index less than that of the top layer of LED die 4, for example, semiconductor layer 8. Hence, a critical angle exists for total internal reflection of light incident on the semiconductor layer 8 / bonding layer 6 interface from inside LED die 4. This critical angle is increased compared to the critical angle for an interface between LED die 4 and epoxy or air, however, and more light is extracted through surface 18 into bonding layer 6 than would be extracted into an epoxy encapsulant or air. In another implementation, the refractive index of bonding layer 6 (for example, ZnS or ZnSe) is greater than or equal to that of semiconductor layer 8 (for example, GaN), and none of the light incident on bonding layer 6 from inside LED die 4 is totally internally reflected. Neglecting Fresnel reflection losses, which can be minimized by approximately matching the refractive indices of bonding layer 6 and the top layer of LED die 4, in the latter case also more light is extracted through surface 18 into bonding layer 6 than would be extracted into an epoxy encapsulant or air.

In another implementation, transparent bonding layer 6 is formed from a low index bonding material, i.e., a bonding material having a refractive index less than about 1.5 at the LED's emission wavelengths. Magnesium fluoride, for example, is one such bonding material. Low index optical glasses, epoxies, and silicones may also be suitable low index bonding materials. One of ordinary skill in the art will recognize that efficient transmission of light from LED die 4 across transparent bonding layer 6, formed from a low index material, to optical element 2 can be achieved if bonding layer 6 is sufficiently thin. Accordingly, in this implementation losses due to total internal reflection at the

LED die 4 / bonding layer 6 interface are reduced by making the thickness of bonding layer 6 less than about 500 Å, preferably less than about 100 Å. Optical element 2 might bond poorly to LED die 4 if the roughness of surface 18 or surface 22 or typical height of irregularities on surface 18 or surface 22 exceed the thickness of bonding layer 6. In this embodiment, surfaces 18 and 22 are optionally polished to achieve a surface roughness of magnitude less than or equal to the thickness of bonding layer 6.

If LED die 4 includes material that absorbs light emitted by active region 12, and if bonding layer 6 is formed from a low index material but is not thin as described above, then a large portion of the light emitted by active region 12 will typically be trapped in LED die 4 and lost to absorption even if bonding layer 6 is itself nonabsorbing. In contrast, a bonding layer 6 formed from a high index material will typically couple a larger fraction of light emitted by active region 12 out of LED die 4 into optical element 2, even if the high index bonding material is a material such as a chalcogenide glass, for example, which absorbs a portion of the emitted light.

After transparent bonding layer 6 is applied to LED die 4, the substantially flat surface 22 of optical element 2 is placed against bonding layer 6. The temperature of bonding layer 6 is then raised to a temperature between about room temperature and about 1000°C, and optical element 2 and LED die 4 are pressed together for a period of time of about one second to about 6 hours at a pressure of about 1 pound per square inch (psi) to about 6000 psi. The inventors believe that in this process optical element 2 is bonded to LED die 4 by a bond effected between optical element 2 and bonding layer 6 (formed on LED die 4) by, for example, material transfer via shear stress, evaporation-condensation, liquification (or melting or softening) followed by solidification, diffusion, or alloying. The inventors believe that in other implementations optical element 2 is bonded to LED die 4 by a bond similarly effected by, for example, material transfer between bonding layers formed on each of optical element 2 and LED die 4 or between bonding layer 6 (formed on optical element 2) and LED die 4. Thus, a bonded interface characterized by material transfer may be disposed between optical element 2 and LED die 4. In one implementation, for example, surface 18 at the interface of n-layer 8 and bonding layer 6 is such a bonded interface. In another implementation, an interface of bonding layers formed on each of optical element 2 and LED die 4 is a bonded interface.

In another implementation, an interface of optical element 2 and bonding layer 6 is a bonded interface.

If transparent bonding layer 6 is formed on LED die 4 from an optical glass, for example, then in one implementation the temperature of bonding layer 6 is raised to about the strain point temperature of the optical glass. The strain point temperature, which is near to but less than the glass transition temperature (T_G), is the temperature at which the optical glass has a viscosity of about $10^{14.5}$ poises. The strain point temperature also corresponds to the first nonlinearity in a plot of expansion versus temperature for the optical glass, and thus represents the lower limit of the annealing range. The resulting flexibility and lowered surface tension of the optical glass in layer 6 at temperatures near or above the strain point temperature allow the optical glass to microscopically conform to surface 22 and to effect a bond between optical element 2 and bonding layer 6.

The process of bonding optical element 2 to LED die 4 described above may be performed with devices disclosed in U.S. Patents 5,502,316 and 5,376,580, incorporated herein by reference, previously used to bond semiconductor wafers to each other at elevated temperatures and pressures. The disclosed devices may be modified to accommodate LED dice and optical elements, as necessary. Alternatively, the bonding process described above may be performed with a conventional vertical press.

Transparent optical element 2 is formed, for example, from SiC ($n \sim 2.7$ at 500 nm), aluminum oxide (sapphire, $n \sim 1.8$ at 500 nm), diamond ($n \sim 2.4$ at 500 nm), or any of the materials listed above for use as bonding materials in transparent bonding layer 6, excluding the metals. A severe mismatch between the thermal expansion coefficients of optical element 2 and LED die 4 to which optical element 2 is bonded can cause optical element 2 to detach from LED die 4 upon heating or cooling. Also, approximately matching thermal expansion coefficients reduces the stress induced in LED die 4 by bonding layer 6 and optical element 2. Hence, in one implementation optical element 2 is formed from a material having a thermal expansion coefficient approximately matching the thermal expansion coefficient of LED die 4 to which optical element 2 is bonded.

In one embodiment, transparent optical element 2 has a shape and a size such that light entering optical element 2 from LED die 4 will intersect surface 24 of optical

element 2 at angles of incidence near normal incidence. Total internal reflection at the interface of surface 24 and the ambient medium, typically air, is thereby reduced. In addition, since the range of angles of incidence is narrow, Fresnel reflection losses at surface 24 can be reduced by applying a conventional antireflection coating 25 to surface

5 24. The shape of optical element 2 is, for example, a portion of a sphere such as a hemisphere, a Weierstrass sphere (truncated sphere), or a portion of a sphere less than a hemisphere. Alternatively, the shape of optical element 2 is a portion of an ellipsoid such as a truncated ellipsoid. The angles of incidence at surface 24 for light entering optical element 2 from LED die 4 more closely approach normal incidence as the size of optical
10 element 2 is increased. Hence, the smallest ratio of a length of the base of transparent optical element 2 to a length of the surface 18 of LED die 4 is preferably greater than about 1, more preferably greater than about 2.

One of ordinary skill in the art will recognize that the maximum size for which an optical element 2 of a particular material continues to be transparent as defined above is
15 determined by the absorption constant of the optical element material at the emission wavelengths of the LED. In one implementation, optical element 2 is a Fresnel lens. Fresnel lenses are typically thinner than, for example, spherical optical elements of comparable focal lengths, and hence are less absorptive.

In some implementations, optical element 2 includes an optical concentrator, for
20 example an optical concentrator using a total internal reflector (TIR). Figure 1D provides an example of an optical concentrator bonded to LED die 4. Although Figure 1D depicts surface 23 of the optical concentrator (optical element 2) as having a parabolic shape, surface 23 may have any shape designed to concentrate light, such as a cone-shape or a beveled shape, and may be coated with metallization or a dielectric material. Active layer
25 12 of LED die 4 is positioned to reduce the amount of light that experiences total internal reflection at surface 24. For example, active layer 12 may be distributed about the focal point of optical element 2. A photon which would have intersected surface 24 at an angle greater than the critical angle in the absence of surface 23 intersects surface 24 at an angle within the critical angle if it first reflects off surface 23. Therefore, surface 23 increases
30 the likelihood of a photon escaping LED die 4.

In yet another implementation, optical element 2 is a graded index optical element having, for example, a refractive index decreasing in the direction perpendicular to surface 22 or decreasing radially from a maximum near a center of surface 22.

Optical element 2 includes, in one implementation, luminescent material that converts light of wavelengths emitted by active region 12 to other wavelengths. In another implementation, a coating on surface 22, for example, includes luminescent material. The luminescent material includes, for example, conventional phosphor particles, organic semiconductors, II-VI or III-V semiconductors, II-VI or III-V semiconductor quantum dots or nanocrystals, dyes, polymers, and materials such as GaN that luminesce from defect centers. Alternatively, a region of optical element 2 near surface 22 is doped, for example, with a luminescent material.

The magnitudes of the refractive indices of optical element 2 ($n_{\text{optical element}}$), bonding layer 6 (n_{bond}), and the top layer of LED die 4 (n_{LED}) can be ordered in six permutations. If $n_{\text{LED}} \leq n_{\text{bond}} \leq n_{\text{optical element}}$ or $n_{\text{LED}} \leq n_{\text{optical element}} \leq n_{\text{bond}}$, then losses due to total internal reflection are eliminated, but Fresnel losses may occur. In particular, if $n_{\text{LED}} = n_{\text{bond}} = n_{\text{optical element}}$, then light enters optical element 2 from LED die 4 without losses due to Fresnel or total internal reflection. Alternatively, if $n_{\text{bond}} \leq n_{\text{LED}} \leq n_{\text{optical element}}$ but either $n_{\text{bond}} > n_{\text{epoxy}}$ or bonding layer 6 is thin as described above, then, neglecting Fresnel reflection losses, more light is extracted into optical element 2 than would be extracted into an epoxy encapsulant or air. Similarly, if $n_{\text{bond}} \leq n_{\text{optical element}} \leq n_{\text{LED}}$ but either $n_{\text{bond}} > n_{\text{epoxy}}$ or bonding layer 6 is thin as described above and $n_{\text{optical element}} > n_{\text{epoxy}}$, then, neglecting Fresnel reflection losses, more light is extracted into optical element 2 than would be extracted into an epoxy encapsulant or air. If $n_{\text{optical element}} \leq n_{\text{bond}} \leq n_{\text{LED}}$ or $n_{\text{optical element}} \leq n_{\text{LED}} \leq n_{\text{bond}}$ but $n_{\text{optical element}} > n_{\text{epoxy}}$, then, neglecting Fresnel reflection losses, more light is extracted into optical element 2 than would be extracted into an epoxy encapsulant or air. Thus, transparent optical element 2 preferably has a refractive index at the emission wavelengths of LED die 4 greater than about 1.5, more preferably greater than about 1.8. A similar analysis applies if the ambient medium is air ($n_{\text{air}} \sim 1$) rather than an epoxy encapsulant, with n_{air} substituted for n_{epoxy} .

If bonding layer 6 includes phosphor particles and the refractive index of the bonding material, preferably a high index chalcogenide glass, approximately matches the

refractive index of the phosphor particles, then scattering by the phosphor particles of light emitted by the active region or by the phosphor particles will be negligible. Preferably, the refractive indices of the phosphor particles, the bonding material, the top layer (for example n-layer 8) of LED die 4, and the optical element are all about equal.

5 This is the case if the top layer of LED die 4 is InGaN, the phosphor particles are SrS:Eu and/or SrGaS:Eu, and the optical element is ZnS.

Referring to Figure 2, in an alternative embodiment transparent optical element 2 is bonded directly to a top surface 18 of LED die 4 without the use of a separate bonding layer. The inventors believe that a bond is effected between optical element 2 and LED

10 die 4 by, for example, material transfer via shear stress, evaporation-condensation, liquification (or melting or softening) followed by solidification, diffusion, or alloying. Metallization layer 20, if present, is patterned to allow surface 22 of optical element 2 to directly contact surface 18. Surface 22 is optionally also patterned by etching, for example. In one implementation of this embodiment, transparent optical element 2 is

15 formed from a material, such as those listed above, which could be used to form a separate bonding layer. In another implementation, the material from which the top layer of LED die 4 (for example, n-layer 8 in Figure 2) is formed is suitable as a bonding material. Thus either optical element 2 or a top layer of LED die 4 functions additionally as a bonding layer, and no separate bonding layer is necessary. In one implementation,

20 the interface of optical element 2 and LED die 4 at surface 18, for example, is a bonded interface characterized by mass transfer between optical element 2 and LED die 4.

For optical element 2 directly bonded to LED die 4, if $n_{LED} \leq n_{optical\ element}$ or if $n_{optical\ element} < n_{LED}$ but $n_{optical\ element} > n_{epoxy}$, then, neglecting Fresnel reflection losses,

25 more light is extracted into optical element 2 than would be extracted into an epoxy encapsulant. A similar analysis applies if the ambient medium is air ($n_{air} \sim 1$) rather than an epoxy encapsulant, with n_{air} substituted for n_{epoxy} .

Transparent optical element 2 is directly bonded to LED die 4 at temperatures and pressures as described above for the bonding process utilizing bonding layer 6. In one implementation, surface 18 of LED die 4 or surface 22 of optical element 2 is doped with

30 a material exhibiting a high diffusivity such as, for example, Zn or Si. Such doping can be accomplished during materials growth by MOCVD, VPE, LPE or MBE, for example,

or after materials growth by, for example, implantation. In another implementation, a thin layer of a high diffusivity material is disposed between optical element 2 and LED die 4 by deposition on at least one of surfaces 18 and 22. Deposition can be accomplished, for example, by conventional means such as evaporation or sputtering.

- 5 The inventors believe that during the bonding process the high diffusivity material diffuses across the interface between optical element 2 and LED die 4 and enhances material transfer between optical element 2 and LED die 4. The amount of high diffusivity material used should be sufficiently low to maintain the transparency of, for example, optical element 2 and the top layer of LED die 4.

- 10 Application of the bonding method is not limited to a pre-made optical element. Rather, transparent optical element 2 may be a block of transparent optical element material that is bonded to LED die 4 in the manner described above, and then formed into optical element 2. Optical element 2 may be formed using etching, perhaps in conjunction with photolithography or other lithographic techniques, electron beam
15 lithography, ion beam lithography, X-ray lithography, or holographic lithography. Wet or dry chemical etching techniques such as plasma etching, reactive ion etching (RIE), and chemically-assisted ion beam etching (CAIBE) may be used as well. Also, optical element 2 may be milled into a surface of the transparent optical element material using ion beam milling or focused ion beam milling (FIB), ablated into the surface with a
20 scanning electron or a laser beam, or mechanically machined into the surface by sawing, milling, or scribing. In addition, optical element 2 may be stamped into the block of transparent optical element material using the method disclosed in U.S. Patent Application Serial No. 09/823,841 which is herein incorporated by reference.

- It is advantageous to bond LED die 4 to optical element 2 rather than to
25 conventionally encase LED die 4 in an encapsulant. For example, the light extraction efficiency through surface 18 of LED die 4 bonded to optical element 2 with or without bonding layer 6, as described above, is improved compared to a conventional epoxy encapsulated LED. In addition, LED die 4 need not be subject to the damaging stress experienced by epoxy encapsulated (encased) LEDs. Moreover, in the absence of epoxy
30 encapsulants, which degrade at relatively low temperatures, LED die 4 can be run at

higher temperatures. Consequently, the light output of LED die 4 can be increased by running the LED at higher current densities.

If desired, however, LED die 4 bonded to optical element 2 could be additionally encapsulated in, for example, epoxy or silicone. Such encapsulation of LED die 4 bonded to optical element 2 would not effect the light extraction efficiency through surface 18 of LED die 4 into optical element 2. Total internal reflection at the interface of surface 24 and the encapsulant would be minimized, as described above, by the shape and size of optical element 2.

In some implementations, LED die 4 includes, for example, metallization for electrical contacts that degrades at elevated temperatures. In other implementations, LED die 4 is bonded to a submount, not shown, with solders or silver bearing die-attach epoxies that degrade at high temperatures. (Note that die-attach epoxy is to be distinguished from an epoxy encapsulant.) Consequently, in one implementation the process of bonding optical element 2 to LED die 4, with or without a bonding layer 6, occurs at temperatures less than about 500°C in order to avoid, for example, degrading the metallization or the die-attach epoxy. In another implementation, optical element 2 is bonded to an incomplete LED die, for example, an LED die missing some or all metallization. In the latter implementation, fabrication of the LED die is completed after the optical element bonding process.

As Figures 3, 4, 5, 6, 7, 8, 9, 10, and 11 illustrate, the structure of LED die 4 may differ from the structure depicted in Figures 1A, 1B, 1C, 1D, and 2. Like reference numbers in Figures 1A, 1B, 1C, 1D, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11 designate the same parts in the various embodiments.

In the embodiment of Figure 3, sides 26 and 28 of LED die 4 are beveled such that they intersect bonding layer 6 at angles α and β , respectively, less than 90° and intersect active region 12 at angles γ and δ , respectively, greater than 90°. Though two beveled sides are shown in Figure 3, in other embodiments LED die 4 has more or less than two beveled sides and is, for example, substantially conical or pyramidal in shape.

Beveled sides 26 and 28 reflect light emitted from active region 12 toward bonding layer 6. Light that might otherwise have been trapped in LED die 4 or lost out the sides of the die is thereby advantageously extracted through bonding layer 6 and optical element 2. In one embodiment, LED die 4 is surrounded by a low refractive index medium such as air, and a portion of the light incident on beveled sides 26 and 28 from active region 12 is totally internally reflected toward bonding layer 6. In another embodiment, beveled sides 26 and 28 are coated with a reflective coating, in one implementation a metal layer and in another implementation a dielectric layer, that reflects light toward bonding layer 6.

In one embodiment, contact 16 is highly reflective. Accordingly, in this embodiment light incident on contact 16 is reflected toward bonding layer 6 and optical element 2 either directly or after additional reflection from side 26 or side 28. The light extraction efficiency of LED die 4 is consequently increased.

In the embodiments illustrated in Figures 4 and 5, LED die 4 includes conducting transparent superstrate 30 electrically coupled to metallization layer 20 and electrically coupled to n-layer 8, and conducting, optionally transparent, substrate 32 electrically coupled to p-layer 10 and to contact 16. Superstrate 30 and (optionally) substrate 32 are formed, for example, from semiconductors having a band gap energy greater than the energy of photons emitted by LED die 4. Superstrate 30 is formed from a material having an index of refraction at the emission wavelengths of active region 12 preferably greater than about 1.5, more preferably greater than about 1.8. In other implementations, sides 26 and 28 of LED die 4 are beveled and highly reflective and contact 16 is highly reflective, as described above. In the embodiment illustrated in Figure 4, transparent optical element 2 is bonded to superstrate 30 with bonding layer 6, and n-layer 8 is electrically coupled to metallization layer 20 by n-contact 14. In the embodiment illustrated in Figure 5, transparent optical element 2 is directly bonded to superstrate 30 and n-contact 14 is not separately provided.

Contact 14 and contact 16 are disposed on the same side of LED die 4 in the "flip chip" embodiments illustrated in Figures 6 and 7. Since optical element 2 is bonded to the opposite side of LED die 4 from contacts 14 and 16, no metallization layer is required on optical element 2 in these embodiments. The light extraction efficiency into optical

element 2 is improved by the absence of the metallization layer. In other implementations, sides 26 and 28 of LED die 4 are beveled and highly reflective and contact 16 is highly reflective, as described above. Transparent superstrate 34 is formed from a material such as, for example, sapphire, SiC, GaN, or GaP, having an index of refraction at the emission wavelengths of active region 12 preferably greater than about 1.5, more preferably greater than about 1.8. In the embodiment illustrated in Figure 6, optical element 2 is bonded with bonding layer 6 to transparent superstrate 34. In the embodiment illustrated in Figure 7, optical element 2 is directly bonded to transparent superstrate 34.

In one implementation of the embodiments illustrated in Figures 6 and 7, optical element 2 is formed from ZnS, superstrate 34 is formed from SiC or GaN, and n-layer 8 is formed from a III-Nitride semiconductor such as GaN. In another implementation, optical element 2 is formed from GaP, superstrate 34 is formed from GaP, and n-layer 8 is formed from a III-Phosphide semiconductor such as an AlInGaP alloy. If present, transparent bonding layer 6 is formed, for example, from ZnS.

In the embodiments illustrated in Figures 8 and 9, the orientation of n-layer 8, p-layer 10, and active region 12 is substantially perpendicular to optical element 2. As in the embodiments illustrated in Figures 6 and 7, no metallization layer is required on optical element 2. In the embodiment illustrated in Figure 8, optical element 2 is bonded with bonding layer 6 to LED die 4. In the embodiment illustrated in Figure 9, optical element 2 is directly bonded to LED die 4. In one implementation, LED die 4 is sawn ("diced") from a wafer with cuts made in a direction substantially perpendicular to layers 8 and 10 and to active region 12. In this implementation, the surface of LED die 4 to be bonded to optical element 2 is optionally polished to reduce its roughness. In other implementations, sides 26 and 28 of LED die 4 are beveled, contact 14 and contact 16 are highly reflective, and reflective layer 36 is located to reflect light into optical element 2.

In the embodiments of Figures 10 and 11, LED die 4 is located in a recess 38 in surface 22 of optical element 2 to which LED die 4 is bonded. In the embodiment illustrated in Figure 10, optical element 2 is directly bonded to LED die 4. In the embodiment of Figure 11, optical element 2 is bonded to LED die 4 with bonding layer 6.

While the present invention is illustrated with particular embodiments, the invention is intended to include all variations and modifications falling within the scope of the appended claims.